INVESTIGATION OF THE ROLE OF ACETABULAR SOFT TISSUE IN THE JOINT BIOMECHANICS OF THE HIP

An Undergraduate Research Scholars Thesis

by

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Submitted to the Undergraduate Research Scholars program at
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by Research Advisor: Dr. Michael R. Moreno

May 2018

Major: Biomedical Engineering

TABLE OF CONTENTS

ABSTRACT

Investigation of the Role of Acetabular Soft Tissue in the Joint Biomechanics of the Hip

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Osteoarthritis causes more than 250,000 hip replacements annually. Hip replacements and other treatments for hip injury cost the United States healthcare system $4 billion each year[1]. Arthritis of the hip joint is typically evaluated via arthroscopy, a minimally invasive endoscopic procedure that involves insertion of a camera and other surgical tools into the joint. This procedure allows direct inspection of the soft tissues of the hip, but requires damage to the joint capsule via a surgical incision (capsulotomy). Repair of the capsulotomy is performed on a case by case basis, with 80% of surgeons routinely leaving the incision unrepaired[2]. The effects of this capsular damage on joint stability are not fully understood, and it is hypothesized that this damage could lead to accelerated deterioration of the joint later in a patient's life. A cadaveric study has been designed to investigate the consequences of capsular damage on the stability of the hip via evaluation of the joint suction seal. A mechanical loading system will be used to break the suction seal within the joint with varying degrees of damage to the joint soft tissue. The load required to break the suction seal for each of these conditions will be recorded and evaluated to demonstrate the role of the hip capsule in the formation of the suction seal of the hip joint.

DEDICATION

All of my work will forever be dedicated to my family. To my parents, thank you for raising me to work hard, be passionate, and always have a curious mind. Megan, thank you for always pushing me, always being there to convince me I'm wrong when I've decided I can't do something. Allison, Katelyn, Sarah – if I can do anything, you can do better. I can't wait to watch y'all succeed in what you love.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Michael Moreno. I've learned and grown so much as an engineer (and as a person) from my time in your lab. A special thank you to Dr. Andrew Robbins – I've learned more from you than from all my classes combined and will forever be grateful to you for putting up with me over the past few years. Thank you to all the graduate students in the lab for making it such an amazing place to be. You all gave me my love for research and thanks to you, I'll never work a day in my life.

I also want to acknowledge and thank our collaborators, Dr. Patrick McCulloch, Dr. Joshua Harris, and their team at Houston Methodist Research Hospital for their many contributions to the study discussed in this work.

CHAPTER I

INTRODUCTION

Background and Motivation for Study

Causes of Injury and Clinical Significance

Conditions such as osteoarthritis cause more than 250,000 hip replacements, or hip arthroplasties, per year[1]. When a patient presents with hip pain and stiffness indicating injuries or pathologies in the joint, it has become common for surgeons to perform hip arthroscopy, allowing them to visualize and treat the joint with minimal invasiveness via endoscopy.

To optimize their access to the joint, surgeons often remove portions of the hip capsule (capsulotomy) or resect all of the capsular tissue (capsulectomy). About 80% of these surgeons do not routinely repair the capsule after capsulotomy, opting to do so only on a case by case basis[2].

Without knowledge on how the condition of capsular tissue affects hip stability and the biomechanics of the joint, medical professionals cannot make fully educated decisions for the treatment of their patients with hip injuries.

Anatomical Context

To allow for easy understanding of the rest of this work, it is important to first discuss the anatomical context it is set in.

The hip bones are part of the pelvis, or pelvic girdle. These bones are jointed posteriorly to the sacrum and anteriorly by the pubic symphysis, a small segment of soft tissue between the ischia. The hip bones are made up of various regions, several of which are relevant and

mentioned throughout the rest of this work. The hip bones and regions described above can be observed in Figures 1 and 2.

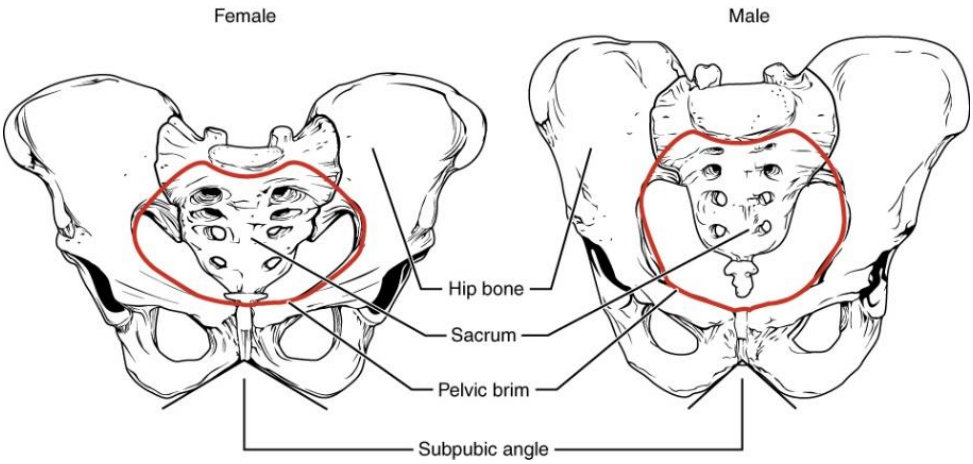

Figure 1. The anatomy of the pelvic girdle.

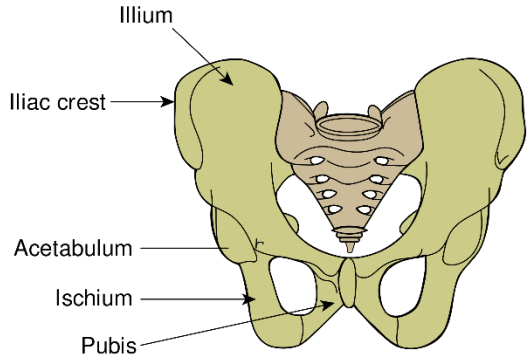

Figure 2. Regions of the hip bone.

The region of the hip bone especially relevant to the hip joint is the acetabulum, the socket that the head of the femur rotates within to provide motion. The joint includes the interface between the femoral head and the acetabulum as well as the soft tissue between them that allows for lubrication and full range of motion without pain.

The acetabulum and the femoral head are covered with articular cartilage that prevents bone-on-bone contact, which causes pain and limits motion. The labrum is a ring of tissue that lines the acetabulum. The joint is wrapped in the articular hip capsule, which is made up of an

inner membrane which secretes fluid to lubricate the joint, and an outer membrane, which provides structural support to the joint. Each of these features can be seen in Figure 3.

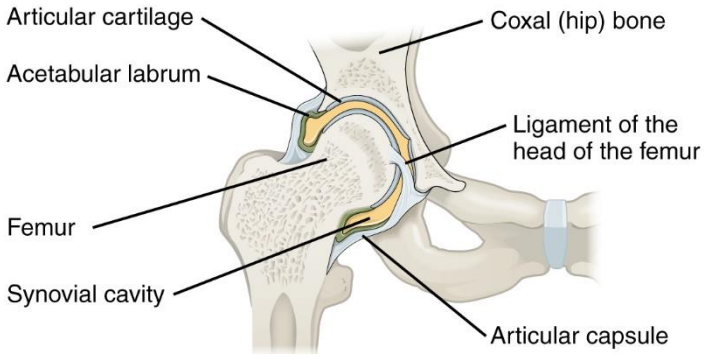

Figure 3. Anatomy of the hip joint.

The fluid secreted by the inner membrane of the articular capsule contributes to the hip fluid seal, which is important for intra-articular fluid pressurization and stability of the joint[3]. It has been found that conditions of various soft tissue components in the hip, such as the labrum, have an effect on the strength of the fluid seal[4]. Without the ability to simulate physiological motion and ambulation in cadaveric specimen, evaluation of the strength of the fluid seal becomes the best metric for evaluation of the stability of the hip.

Objectives

Studying the mechanics of the hip before and after capsulotomy, capsular repair, and capsulectomy can isolate the role of the capsule in hip joint stability and aid in decision making for patients with hip injury. The objectives for this work include development of testing fixtures and mechanical testing protocol for evaluating the strength of the fluid seal in cadaveric specimens with and without damage to the capsule and before and after repair of this damage to isolate its effects on the stability of the hip joint.

CHAPTER II

METHODS

Specimen Preparation

Ten human cadaveric specimens from the L1 vertebra to the distal end of the femurs were provided by collaborators at Houston Methodist Research Hospital. These specimens were received fresh frozen and stored at -20°C until five days before testing, when they were set out at +4°C to thaw. Thermocouples were implanted in the soft tissue of each specimen so temperature could be monitored during thawing.

Once thawed, all soft tissue will be removed from the specimen except the hip capsule and the tissue inside of it that play a direct role in the hip joint. The halves of the pelvis will be separated and the iliac portion removed. Figure 4 shows the geometry of the specimens after dissection at the time of testing, as well how it would be held in fixtures during testing.

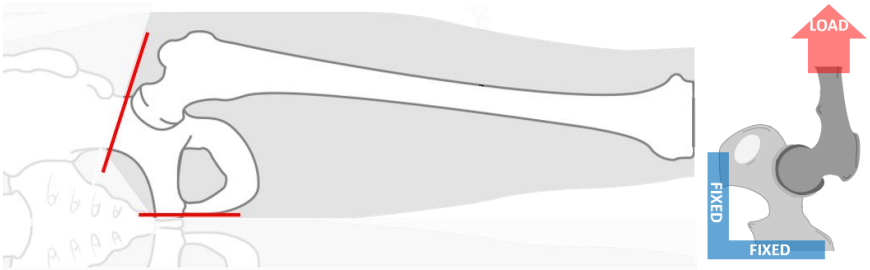

Figure 4. Specimen geometry (left) and loading position (right) during testing

Fixture Development

Development of fixtures was required so specimen could be mounted and tested with minimal introduction of unpredictable factors. To accomplish this, a list of design requirements was produced to ensure all user needs were addressed.

Fixture Design Requirements

The hip is a ball and socket joint, which allows for a wide range of motion, as shown in Figure 5. Abduction involves moving the leg away from the opposite leg while remaining in plane with the body, while adduction involves moving the leg towards the opposite leg. Flexion occurs when the leg is moved towards the front of the body, and extension occurs when the leg is moved towards the back. To address this range of motion, it was required that the fixtures allow rotational adjustment in both directions that could be precisely set before and between tests.

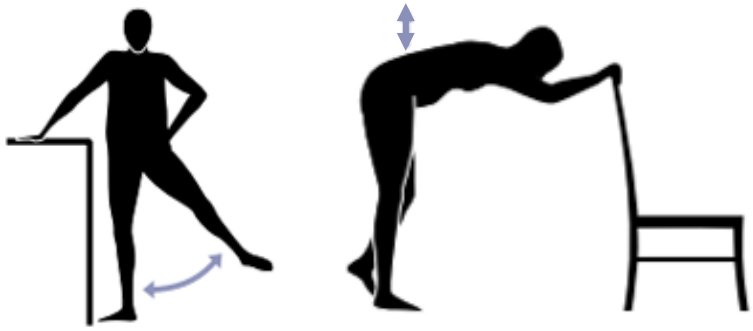

Figure 5. Range of motion of the hip, including abduction/adduction (left) and flexion/extension (right).

The specimens were expected to be moist and maintain some soft tissue, so fixtures needed to be able to grip onto them and prevent slipping. Specimen were also expected to vary in specific geometry, so fixtures needed to be somewhat adjustable in order to function across this variability.

Lastly, these fixtures needed to be able to interface with a previously developed reconfigurable testing system (RTS), which was designed to be configured for various mechanical tests on joints, biomaterials, biological tissues, and other kinds of specimen.

Design Iterations

Many designs were considered during the process of fixture development. Two sets of fixtures were produced: one for fixing the remaining hemipelvis, and one for fixing the distal end

of the femur. Primary reasons for rejecting designs were (1) overall cost and (2) difficulty of manufacturing.

Development of the pelvic fixture is shown in Figure 6. The original design of the framing allowed for simulated range of motion (purple units), but manufacturing of the parts would have been complex and time consuming. Also, once manufactured, there would have been no room for adjustment to address variances in specimen geometry. The final design, composed of aluminum extrusions and accessories from 80-20, linear stages (red) and rotational stages (green) from ThorLabs, and various aluminum components to customize the system, allowed full adjustability before and between tests.

The hemipelvis would be mounted to the post on top of the linear stages. Holes would be drilled into the bone and then screws would be passed through into the post, which has many holes to allow for varying hole placement in varying geometries of bone. Once mounted, the linear stages could adjust the position of the bone within the system, to ensure that the center of the hip joint was aligned with the load application during testing. The rotational stages could be adjusted to allow for simulation of abduction/adduction and flexion/extension. The use of the 80-20 extrusions allowed for height and width adjustment of the system, if necessary.

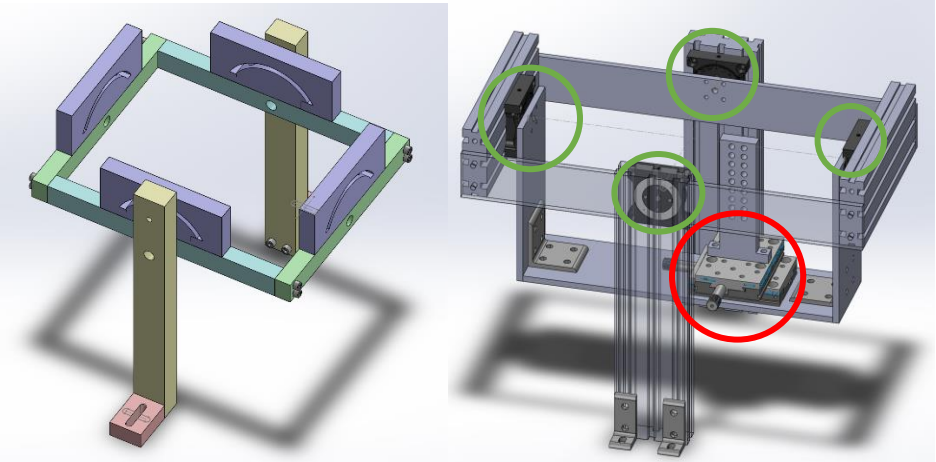

Figure 6. Development of pelvic fixture (Left: Original design of framing. Right: Final design).

The 80-20 extrusions also allowed the system to be adjusted so it could interface with the RTS, which is outfitted with a large ThorLabs optical breadboard. The RTS is shown with the final pelvis fixture in Figure 7.

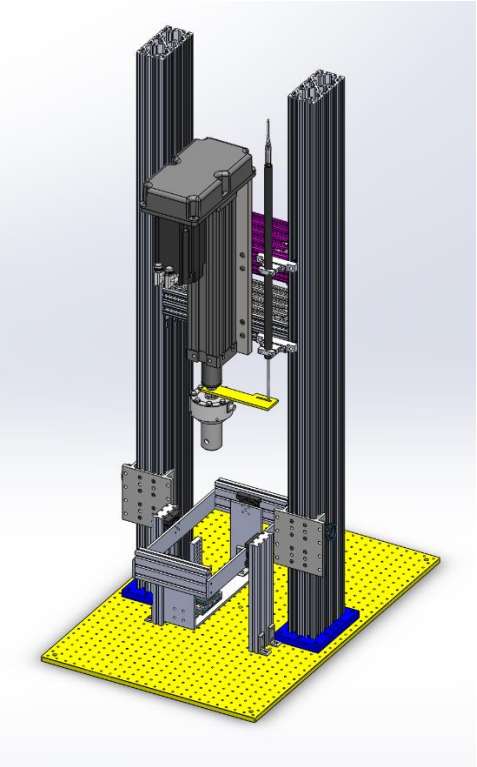

Figure 7. RTS with pelvic fixture mounted to ensure successful interfacing between systems.

The femoral fixture underwent several more design iterations. The development of this design is shown in Figure 8.

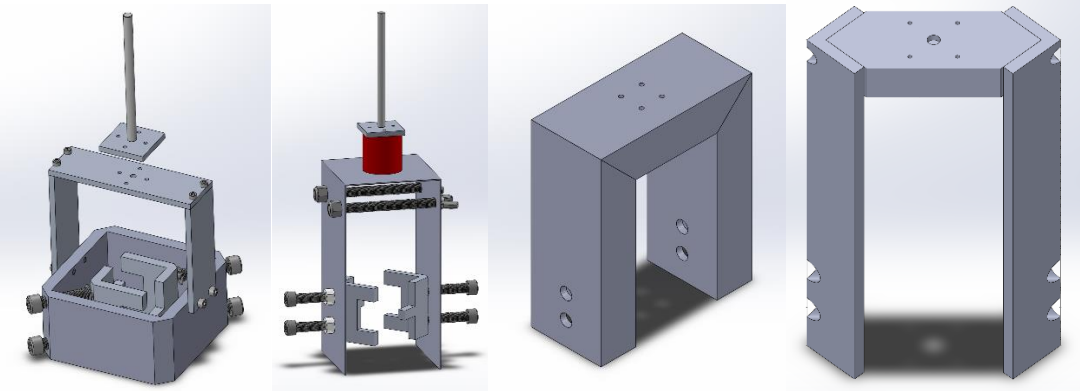

Figure 8. Design development of femoral fixture.

During the design process of the femoral fixture, minimal fixture weight became a design requirement. The original design included the use of interior clamps that would apply pressure to the femur as they were tightened into the housing. This technique worked well and was maintained throughout later design iterations, although it is not shown in their renderings in Figure 8. However, the original clamp housing required complex machining, inhibited access to the specimen during testing, and would have weight too much to suspend from the load cell used for testing and still be able to safely apply the desired amount of loading to the joint.

The second design simplified machining and increased accessibility to the specimen but was not structurally sound. When tested on bone models, significant bending was observed and prevented rigid fixation. Attempting to solve this issue by increasing wall thickness caused the weight to increase too much, so the third design was produced to address this design flaw.

The third design was manufactured using rectangular aluminum tubing of various width, depth, and wall thickness. Small amounts of bending were still observed, and weight and overall size made it non-ideal.

The fourth and last design, manufactured from aluminum, was composed of a top segment of aluminum tubing cut and welded to aluminum 90 degree angle irons. This design significantly reduced bending, and the weight and overall size made it easy to handle and test with. The final pelvis and femoral fixtures were manufactured, assembled, and used in pilot tests using artificial bone analogues from Sawbones.

Loading Protocol

Once fixture designs were developed, a loading protocol was developed to plan how the joint would be loaded once mounted in the system.

An approximation of the loading protocol is shown in Figure 9. Loads below the **time** axis indicate compression and loads above the **time** axis indicate applied tension in the joint. Displacements below the **time** axis indicate that the femoral head is closer to the acetabulum than it is in the starting position, while displacements above the **time** axis indicate that it is further away.

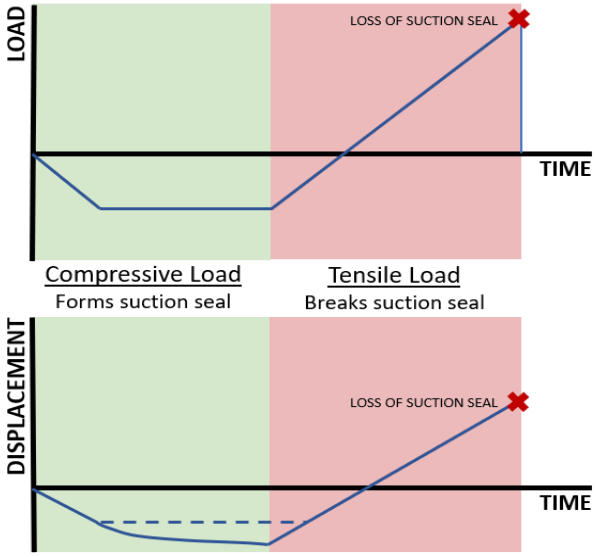

Figure 9. Planned loading protocol.

After being mounted into the system, an initial compressive load would be applied to ensure the suction seal is fully formed. Due to the mechanical properties of biological tissue, it would be expected that the tissue in the joint would relax under the applied load, requiring further displacement of the femora head into the acetabulum to maintain the load.

After a fixed period of time, the compressive load would be removed and the femur would be pulled up out of the acetabulum a fixed distance, large enough to break the suction seal but small enough to prevent tearing of any soft tissue in the joint. Before the suction seal breaks, this displacement would increase the load on the joint, but once it is broken, the load should drop

drastically. This effect is similar to pulling a suction cup off of a smooth surface: it requires more and more force to remove it, but once its seal is broken, it is easily removed from the wall.

Mechanical Testing

Once fixtures and the loading protocol had been developed, a full mechanical testing procedure could be planned. The full testing system, including fixtures, load cell, and artificial bone analogues, is shown in Figure 10.

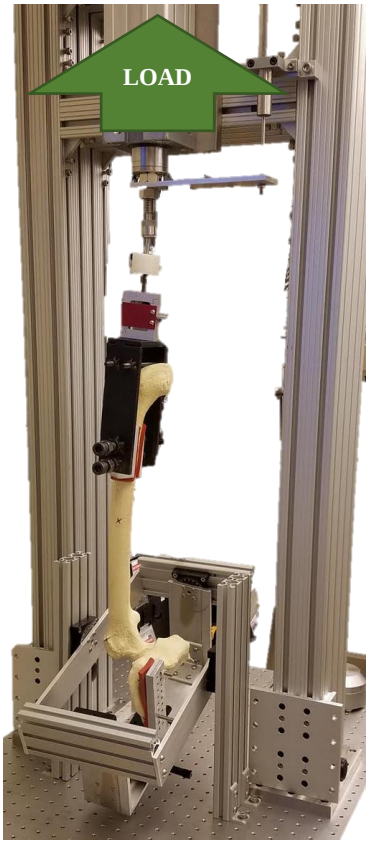

Figure 10. Bone analog mounted into testing carriage and fixed to RTS via femoral clamp, showing the direction of load application during testing.

Both joints from ten cadaveric specimens provided by Houston Methodist Research Hospital would be mounted in the system as shown in Figure 10. The loading protocol would be applied once to a specimen with an intact joint capsule. In several specimens, the intact joint capsule would be tested multiple times. If the responses are determined to be the same, then we

can be sure that no tissue is being damaged during testing and presenting an unknown variable into our data.

After the intact capsule is tested, surgeons from Houston Methodist would perform a capsulotomy and the loading protocol would be repeated. The damage from the capsulotomy would be repaired, and the joint would be tested again. The joint would be tested a final time after full capsulectomy had been performed.

Some of these tests would be performed multiple times in a variety of abduction/adduction and flexion/extension angles, as listed in Table 1. These angles would be determined based off of physiological angles in common positions and activities.

Table 1. Angles of abduction/adduction and flexion/extension studied during testing

Configuration	**Flexion/Extension**	**Abduction/Adduction**
1	Neutral (0°)	Neutral (0°)
2	45° Flexion	Neutral (0°)
3	10° Extension	Neutral (0°)
4	Neutral (0°)	45° Abduction
5	Neutral (0°)	10° Adduction

CHAPTER III

PILOT TESTING

Results

Pilot testing was performed with artificial bone analogues mounted into the fixtures on the RTS as shown in Figure 10. The suction seal was simulated using adhesive padding set into the joint. Loading and displacement versus time are shown in Figure 11.

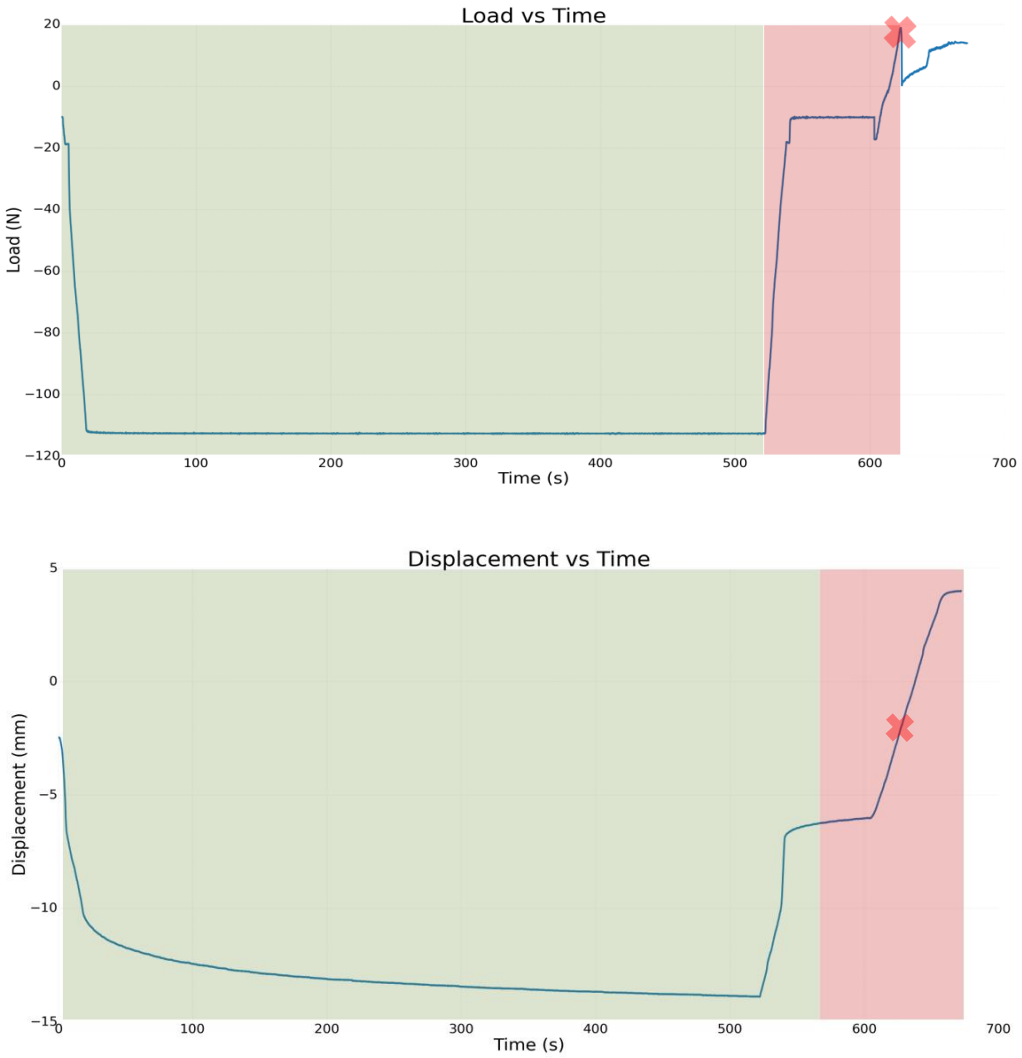

Figure 11. Load vs time (top) and displacement vs time (bottom) plots from pilot testing.

Discussion

The load vs. time plot in Figure 11 shows the compression down to a fixed load which is held for a fixed period of time to ensure that the suction seal (adhesion in the padding) is fully formed. In the corresponding displacement response, the relaxation of the padding can be observed, which is also predicted in the soft tissue during future testing. The load is then removed, although a slight compressive load is maintained to keep the padding adhered within the joint.

The RTS was then transitioned into displacement control, and the femur was displaced from the acetabulum by a fixed amount. This applied a tensile load to the adhesive padding, causing the load to increase drastically before the padding came apart within the joint (indicated by the red "x" in the plot), causing a steep drop in load.

This pilot testing shows that our fixtures and loading protocol are plausible and we are ready to move forward with testing of human cadaveric specimen.

CHAPTER IV

CONCLUSION

A study has been planned to evaluate the effects of varying degrees of capsular damage on the strength of the suction seal in the hip. Fixtures have been designed and manufactured for use in a reconfigurable mechanical testing system, and a loading protocol has been developed. Both have been tested successfully using artificial bone analogues.

Three cadaveric specimens have been procured from Houston Methodist Research Hospital, and seven more will be provided. These specimens will be mounted into the testing system via the fixtures, and the loading protocol will be applied at various physiologically relevant angles and various levels of capsular damage.

This data will be analyzed to determine the effects of capsulotomies (both repaired and unrepaired) and capsulectomies on the stability of the hip joint. This study will produce more knowledge about the mechanics of the hip joint and provide surgeons and other clinicians with new information so they can make educated decisions about the treatment of their patients with hip injury.

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